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Iterative Receiver in Time-Frequency Domain for Underwater Acoustic Communications

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Abstract

In this paper, we combine soft MMSE equalization method, and the serially concatenated trellis coded modulation (SCTCM) decoding to develop an iterative receiver in time-frequency domain (TFD) for SC underwater acoustic point to point communications. This iterative procedure can reduce the calculation complexity of equalization and obtain better performance using less receiving elements. Finally, we use sound speed profile (SSP) measured in the lake and Bellhop model to simulate underwater channel to verify the performance of the proposed receive algorithms.

Keywords: Frequency domain equalization (FDE), Iterative receiver, Serially concatenated trellis coded modulation (SCTCM), Single Carrier (SC), Underwater Acoustic Communications;

1. Introduction

The underwater acoustic communication channel is a time varying, space-varying, frequency-varying variable parameter channel with serious multi-path time delay, frequency selective fading and the limited bandwidth [1]. An effective approach to eliminate the inter-symbol interference (ISI) caused by multi-path propagation is that adaptive decision feedback equalizer (ADFE) which is applied in [2-3] represents a more general approach to spatial and temporal signal processing. Meanwhile, channel coding is an effective technology to ensure reliable data transmission. So, an iterative equalization and decoding (IED) [4] has been developed combining ADFE and decoder to obtain reliable data transmission. But, it usually

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needs complex equalization algorithm and more receiver arrays in order to obtain satisfied data transmission especially in shallow water.

For channels with severe delay spread, such as underwater acoustic channel, frequency domain equalization (FDE) is computationally simpler than corresponding time domain equalization because equalization is performed on a block of data at a time and the operations on this block involve an efficient FFT operation and a simple channel inversion operation. A single carrier (SC) system with FDE (SC-FDE) has essentially the same performance and low complexity as an OFDM system when combined with FFT processes and the use of a cyclic prefix (CP) or zero padding (ZP). In addition, the use of SC modulation and FDE by processing the FFT of the received signal has the following attractive features [5-6]: (1) SC modulation can reduce peak-to-average ratio (PAR) requirements from OFDM, thereby allowing the use of less costly power amplifiers; (2) Its performance with FDE is similar to that of OFDM, even for very long channel delay spread; (3) Frequency domain receiver has a similar complexity reduction advantage to that of OFDM, that is complexity is proportional to log of multipath spread.

In this paper, a SC transmission system with iterative time-frequency domain receiver, based on FDE and time domain serially concatenated trellis coded modulation (SCTCM) decoding, is developed. The FDE is designed based on minimum mean squared error (MMSE) equalization with a priori information [7] and implemented in frequency domain with least square (LS) channel estimation. In proposed iterative receiver, on the one hand, the performance of equalizer can be enhanced utilizing decoding gain provided by SCTM decoder; on the other hand, we can use simpler equalization processing and less receiving elements to obtain reliable data transmission.

2. Signal and System Models

In this paper, we focus on a coded communication system exploiting iterative equalization and decoding techniques at the receiver side. Its transmitter structure is obtained by inserting a SCTCM encoder before the PSK symbol mapping, and the inner encoder together with the symbol mapping to construct the TCM structure. The structure of transmitter is shown in Fig.1. For MPSK, let's define $m = \log_2 M$, where, M is number of phases. In comparison with high performance PCTCM scheme [8], the method in [9], with lower complexity, is adopted to design SCTCM, which can achieves $km/\ k+1$ bit/s/Hz, using a rate $R_0 = k/k+1$ convolutional encoder with maximum free hamming distance as the outer encoder. The interleaved data enters a rate $R_i = m/m = 1$ recursive convolutional inner encoder. The m output bits are then mapped to one symbol belonging to a 2^m level modulation.

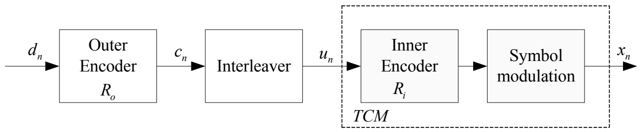

Fig.1 The structure of transmitter

At the receiver, a soft input soft output (SISO) FDE is connected, in a feedback loop, to a SISO channel decoder. The latter generates both data a posteriori probabilities (APPs) and hard data decisions on the basis of a set of soft data produced by the former; the APPs are sent back to the equalizer as a priori probabilities, with the aim of adjusting its filters. The algorithms for iterative receiver are analyzed in the next section.

3. Iterative Equalization and Decoding in Time-Frequency Domain (TFD)

The block diagram of the proposed iterative receiver is illustrated in Fig.2. In its *l*th iteration, the received vector feeds to the MMSE equalizer. This produces the vector feeding an IDFT. The IDFT output vector is applied to a SISO SCTCM decoder producing the data APPs, which are exploited to generate the extrinsic information. This is then processed to produce a soft estimate of the ISI in the received signal samples, and to adjust the MMSE equalizer for the next iteration.

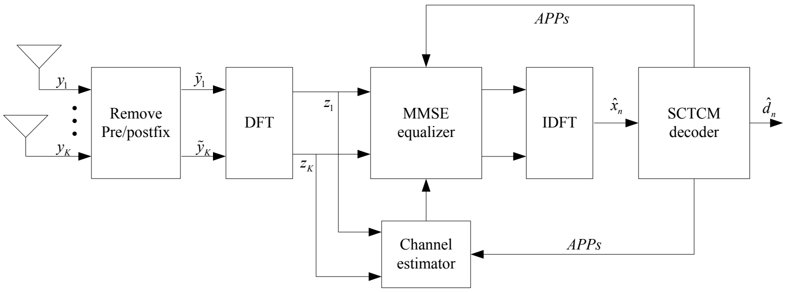

Fig.2 Block diagrams of the iterative receiver in TFD

In this section, we first derive MMSE equalization using a priori information in FD. And then, an iterative receiver based on equalization and SCTCM decoder is developed. As shown in Fig.2, the space diversity technology is adopted.

3.1. Iterative Channel Estimation

Underwater acoustic channel has the large delay spread, thus the cycle prefix (CP) portion would consume a considerable fraction of the transmission power. So, in this paper, we adopt zero padding (ZP) manner to construct data frame like as ZP-OFDM [10]. And then, we adopt the low-complexity overlap-add (OLA) processing on the received signals. The OLA can convert a linear convolution into a circular convolution such that the FFT can be used to process the received signals.

In this paper, we use the Zadoff-Chu (Z-C) sequences as training to estimate the channel. So, we can find the channel estimation based on the least square (LS) formulation

$$\underbrace{\begin{bmatrix} z_1 \\ \vdots \\ z_{K_t} \end{bmatrix}}_{:=\mathrm{z}} = \underbrace{\begin{bmatrix} \omega_1 \\ \vdots \\ \omega_{K_t} \end{bmatrix}}_{:-\omega} + \underbrace{\begin{bmatrix} s_1 & & \\ & \ddots & \\ & & s_{K_t} \end{bmatrix}}_{:-\mathrm{S}} \underbrace{\begin{bmatrix} 1 & e^{j\frac{2\pi}{K_t}} & \cdots & e^{j\frac{2\pi}{K_t}\, L\ \ 1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{j\frac{2\pi}{K_t}\, K_t\ \ 1} & \cdots & e^{j\frac{2\pi}{K}\, K_t\ \ 1\ \ L\ \ 1} \end{bmatrix}}_{:-\mathrm{V}_{K_t\times L}} \underbrace{\begin{bmatrix} h_0 \\ \vdots \\ h_{L\ \ 1} \end{bmatrix}}_{:-\mathrm{h}} \tag{1}$$

where, z_t is the received training after FFT, $\mathrm{s}_t=\mathrm{fft}\ \ \mathrm{x}_t$ denotes the transmitted training after FFT, $\mathrm{V}_{K_t\times L}$ is vandermonde matrix, h denotes the channel impulse response with *L* coefficients.

So, the least square (LS) estimation of h is

$$\hat{\mathrm{h}}_{LS} = \arg\min_{\mathrm{h}} \left\| \mathrm{z}_t - \mathrm{S}_t \mathrm{V}_{K_t\times L} \mathrm{h} \right\| = \ \mathrm{V}_{K_t\times L}^{H} \mathrm{S}_t^{H} \mathrm{S}_t \mathrm{V}_{K_t\times L}\ ^{-1}\ \mathrm{V}_{K_t\times L}^{H} \mathrm{S}_t^{H} \mathrm{z}_t \tag{2}$$

During the iteration procedure, we can utility the soft information feedback from the decoder to get the estimation of the transmitted symbols. And then, we have the iterative channel estimation according to LS scheme

$$\hat{\mathrm{h}}_{LS} = \left(\mathrm{V}_{K_t\times L}^H \mathrm{S}_t^H \mathrm{S}_\mathrm{t} \mathrm{V}_{K_t\times L} + \mathrm{V}_{K_d\times L}^H \mathrm{S}_d^H \mathrm{S}_\mathrm{d} \mathrm{V}_{K_d\times L}\right)^{-1} \left(\mathrm{V}_{K_t\times L}^H \mathrm{S}_\mathrm{t}{}^H \mathrm{z}_\mathrm{t} + \mathrm{V}_{K_d\times L}^H \hat{\mathrm{S}}_\mathrm{d}{}^H \mathrm{z}_\mathrm{d}\right) \tag{3}$$

where, z_t and z_d are the received training and information symbols in frequency domain (FD) respectively. S_t and $\hat{\mathrm{S}}_d$ denote the transmitted training and estimated information symbols in FD respectively. $\hat{\mathrm{S}}_d$ can be obtained from the (20) and (21) in section *3.3*.

Once the channel estimation $\hat{\mathrm{h}}_n, n = 1,\cdots,N_r$, are available, the channel frequency response on each information symbol k is evaluated as

$$H_n(k) = \sum_{l=0}^{L-1} h(l) e^{-j\frac{2\pi}{K_t}kl}, \quad k = 0,\cdots,K_t - 1 \tag{4}$$

3.2. Iterative Frequency Domain Equalization (FDE) and Decoding

On each data symbol, the information symbols from receiving elements after FFT is grouped into a vector $z_k = \left[z_1(k),\cdots,z_{N_r}(k)\right]^T$, and h_k denotes the $N_r \times 1$ channel frequency response for kth symbol, $s(k)$ is the FD value of the transmitted symbol $x(k)$. Thus, we have

$$\underbrace{\begin{bmatrix} z_1(k) \\ \vdots \\ z_{N_r}(k) \end{bmatrix}}_{:=\mathrm{z}_k} = \underbrace{\begin{bmatrix} H_1(k) \\ \vdots \\ H_{N_r}(k) \end{bmatrix}}_{:=\mathrm{h}_k} s(k) + \underbrace{\begin{bmatrix} \omega_1(k) \\ \vdots \\ \omega_{N_r}(k) \end{bmatrix}}_{:=\omega_k} \tag{5}$$

In this paper, the MMSE equalization algorithm with a priori information [7] is applied. But, we carry it out in FD according to (5). The inputs to the MMSE equalizer are z_k and estimate channel frequency response h_k, and the APPs of the transmitted symbols delivered by SCTCM decoder. The outputs of the MMSE equalizer are the probabilities of each information symbol being equal to one valid constellation point.

The FD estimate $\hat{s}_k$ of the transmitted information symbol x_k is given by

$$\hat{s}_k = \mathrm{w}_k^H \mathrm{z}_k + \mathrm{b}_k \tag{6}$$

Where, w_k and b_k are the coefficient vectors of the estimator.

We choice

$$\begin{cases} \mathrm{w}_k = \mathrm{cov}(\mathrm{z}_k,\mathrm{z}_k)^{-1} \mathrm{cov}(\mathrm{z}_k, s_k) \\ \mathrm{b}_k = E(s_k) - \omega_\mathrm{k}^\mathrm{H} E(\mathrm{z}_k) \end{cases} \tag{7}$$

minimizes the cost $E\left(|s_k - \hat{s}_k|^2\right)$, and we can get the MMSE solution

$$\hat{s}_k = E(s_k) + \mathrm{cov}(s_k,\mathrm{z}_k)\,\mathrm{cov}(\mathrm{z}_k,\mathrm{z}_k)^{-1}\left(\mathrm{z}_k - E(\mathrm{z}_k)\right) \tag{8}$$

According to (5), we find that

$$E(\mathrm{z}) = \mathrm{h}_k E(s_k) \tag{9}$$

$$\mathrm{cov}(s_k,\mathrm{z}_k) = \mathrm{cov}(s_k,s_k)\,\mathrm{h}_k^H \tag{10}$$

$$\mathrm{cov}(z_k,z_k) = \sigma_\omega^2 I_K + \mathrm{h}_k\,\mathrm{cov}(s_k,s_k)\,\mathrm{h}_k^H \tag{11}$$

where, $E(s_k)$ and $\mathrm{cov}(s_k, s_k)$ are the mean and variance of the transmitted symbol s_k in FD, which are can be computed as follows

$$\bar{s}_k \triangleq E(s_k) = \sum_{\alpha_i \in B} \alpha_i \cdot P(s_k = \alpha_i) \tag{12}$$

$$\upsilon_k \triangleq \mathrm{cov}(s_k, s_k) = E\left(|s_k|^2\right) - |\bar{s}_k|^2 \tag{13}$$

where, $P(s_k = \alpha_i)$ can be obtained from the APPs delivered from SCTCM decoder.

We define

$$\Sigma \triangleq \mathrm{cov}(z_k, z_k) = \sigma_\omega^2 I_K + \mathrm{h}_k \upsilon \mathrm{h}_k^H \tag{14}$$

$$\mathrm{f_k} \triangleq \Sigma^{-1} \mathrm{h}_k \tag{15}$$

$$G_n \triangleq \left(1 + (1 - \upsilon_k)\, \mathrm{f_k^H h}_k\right)^{-1} \tag{16}$$

So, the estimate $\hat{s}_k$ is given by

$$\hat{s}_k = G_n \mathrm{f_k^H} \left(\mathrm{z}_k - \bar{\mathrm{z}}_k + \bar{s}_k \mathrm{h}_k\right) \tag{17}$$

After IDFT, we can get time domain (TD) transmitted symbol $\hat{x}_k$, which will be send to the SCTCM decoder to generate the final bits decision $\hat{d}_k$ and the APPs of transmitted symbols for next iteration.

3.3. SCTCM Decoding

As mentioned above, the output vector after IDFT is applied to a SISO SCTCM decoder producing the data APPs, which are exploited to generate the extrinsic information. This is then processed to produce a soft estimate of the ISI in the received signal samples, and to adjust the MMSE equalizer for the next iteration. The decoding algorithm of SCTCM can see [4, eq. (11) ~ (17)].

From (12) and (13), we need know the probability $P(x_k = \alpha_i)$ of the transmitted symbols x_k to update the coefficient of MMSE equalizer during the iterative procedure. The probability $P(x_k = \alpha_i)$ is the function of a priori information $L(d_{k,i})$ delivered by SCTCM decoder, and thus

$$P(x_k = \alpha_i) = \prod_{i=1}^{m} P(d_{k,i}) \tag{18}$$

$$P(d_{k,i}) = \frac{e^{d_{k,i} \cdot L(d_{k,i})}}{1 + e^{L(d_{k,i})}} \tag{19}$$

where, $\alpha_i \in \mathrm{B}$, $\mathrm{B} = \{\alpha_1, \alpha_2, \cdots, \alpha_M\}$ denotes the finite alphabet used for MPSK, $d_{k,i}$ denotes the *i*th coded bit of the *k*th transmitted symbol, $i = 1, 2, \cdots \log_2 M$.

Using (18), (19) and DFT, (12) can be rewritten as

$$\bar{s}_k \triangleq E(s_k) = \sum_{i=0}^{K-1} E(x_k) \times \exp\left(-j \frac{2\pi k i}{K}\right) \tag{20}$$

where

$$E(x_k) = \sum_{\alpha_i \in B} \alpha_i \cdot P(x_k = \alpha_i) \tag{21}$$

In addition, the value from (20) can as the symbol estimation feedback to channel estimator to aid iterative channel estimation.

4. Simulation Results

In this section, we use sound speed profile (SSP) measured in the lake and Bellhop model to simulate the underwater acoustic channel to verify the performance of the proposed iterative receiver.

4.1. Simulation Model and Parameters

In our communication systems, QPSK modulation is adopted. The carrier frequency and the sample frequency are 10 KHz and 40 KHz respectively. The code rate is 1/2. Four receiving elements are adopted for spatial diversity. The symbol rate of communication system is 10 Ksps.

The SSP and channel impulse responses (2000m) are shown in Fig.3 and Fig.4 respectively. From Fig.3, we know that the water deep is about 53m with mixed gradient. As shown in Fig.4, there are large spread delays for underwater acoustic channel.

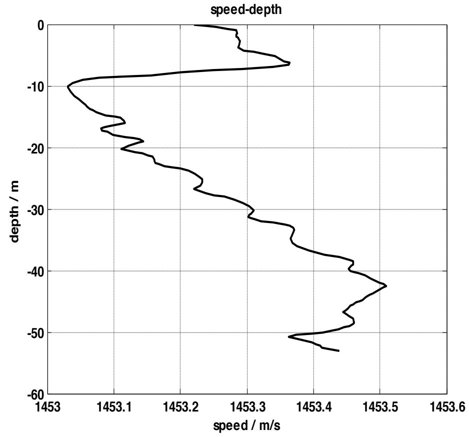

Fig.3 Sound speed profile (SSP)

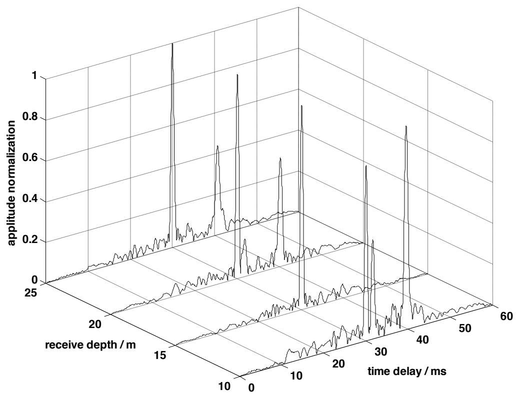

Fig.4 Channel impulse response

4.2. the Performance of Iterative Receiver

Fig.5 shows the BER curves of iterative receiver in TFD using four receiving elements for QPSK modulation. As show in Fig.5, the iterative receiver in TFD can sufficient utilize the decoding gain provided by decoder of SCTCM to enhance the equalizer performance such that the system performance is increased and the data transmission with lower BER can be obtained.

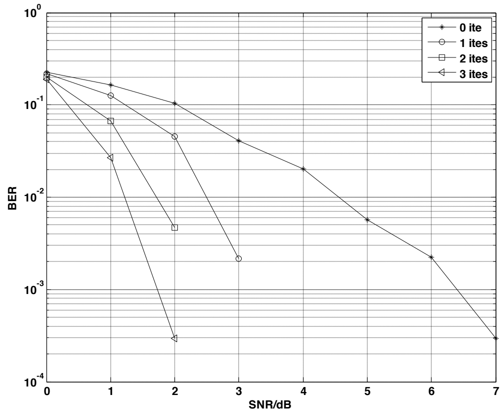

Fig. 5 the performance of iterative receiver

5. Conclusions

In this paper, a SC transmission system with iterative receiver in TFD, based on FDE and time domain SCTCM decoding, is developed. The FDE is designed based on minimum mean squared error (MMSE) equalization with a priori information and impleminented in frequency domain with least square (LS) channel estimation. In proposed receiver scheme, on the one hand, the performance of equalizer can be enhanced utilizing decoding gain provided by SCTCM decoder; on the other hand, we can use simpler equalization processing and less receiving elements to obtain reliable data transmission to satisfy the knots requirements of point-to-point communications. The simulation results verify the proposed iterative receive can obtain satisfied data transmission using less receiving elements.

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